

RADIOFREQUENCY TRANSMITTER WITH A HIGH DEGREE OF
INTEGRATION AND POSSIBLY WITH SELF-CALIBRATING IMAGE

DELETION

Field of the Invention

The field of the invention is that of transmitting signals by a frequency channel.

BACKGROUND

It will be recalled that transmission of a signal
5 by a frequency channel more and more often calls upon digital modulation, the main advantage of which is that it permits the use of signal processing algorithms. The purpose of these algorithms is to increase the strength of the signal to be transmitted relative to the
10 propagation channel.

SUMMARY

More precisely, the invention relates to a radiofrequency transmitter of the type supplied by two signals (or components) in baseband and in quadrature $i(t)$ and $q(t)$, which are images of two binary streams
15 representing a piece of information to be transmitted. In effect, whatever the type of digital modulation, the signal to be transmitted $m(t)$ can be written :

$m(t) = i(t) \cdot \cos(\omega t) - q(t) \cdot \sin(\omega t)$, where $\omega (=2\pi f)$ is the transmission frequency of the signal (also called the carrier frequency).

In the state of the technology, different types of radiofrequency transmitter are known, each based on a distinct architecture. The most widely known are the radiofrequency transmitter with frequency transposition, the radiofrequency transmitter with direct conversion and the radiofrequency transmitter with a phase locked loop. Their respective disadvantages will now be discussed.

The radiofrequency transmitter with frequency transposition which permits transposition to an intermediate frequency FI, requires the use of selective pass band filters, so as to reject the image frequency of the wanted signal to be transmitted. This first type of radiofrequency transmitter provides good performance, thanks to frequency transposition into the digital domain. However, the requirement to use high performance filters restricts its degree of integration onto silicon.

The radiofrequency transmitter with direct conversion has the most simple architecture and offers a high degree of integration. Its weak point is its high sensitivity to the performance of the elements that make it up. In particular, it is recommended that any leakage from the conversion oscillator via the mixer be avoided or that provision is made for perfect quadrature of the sine and cosine signals. These imperatives are often difficult to keep to.

The radiofrequency transmitter with a phase locked loop offers numerous advantages, such as the ability to do away with RF filters thanks to the pass band characteristic of the phase locked loop or PLL. The requirement to have the signals strictly in quadrature is also avoided. Nevertheless, these results are only possible if the voltage controlled oscillator or VCO included in the PLL provides high performance. This is not the case with integrated VCOs. Consequently, the PLL radiofrequency transmitter does not enable a high level of integration to be provided.

Therefore in a general way, these three types of known architecture offer a necessary compromise between integration, consumption and complexity. In other words, none of these three known solutions is entirely satisfactory.

A particular objective of the invention is to remedy these various disadvantages of the state of the technology.

More precisely, one of the objectives of this invention is to provide a radiofrequency transmitter providing good precision and offering a very high degree of integration on silicon.

Another objective of the invention is to provide such a radiofrequency transmitter that has very low sensitivity to the imperfections in the elements that make it up.

Another objective of the invention is to provide such a radiofrequency transmitter that enables one to avoid degradation of the wanted signal.

A complementary objective of the invention is to provide such a radiofrequency transmitter which is simple and is not any more complex than the known architectures.

5 Another objective of the invention is to provide such a radiofrequency transmitter that allows one to generate a resultant signal that has an image frequency that is sufficiently weak to be able to be suppressed by a filter with relaxed constraints (this filter thus
10 being capable of being integrated).

In an embodiment variation, another objective of the invention is to provide a radiofrequency transmitter that does not give an image frequency, the image frequency at the output being completely attenuated, in
15 an automatic fashion, by a self-calibrating system that compensates for imperfections both in gain and in phase.

These various objectives as well as others that will become apparent below, have been achieved according to the invention by a radiofrequency transmitter, of the
20 type supplied with two signals in baseband and in quadrature, $i(nT)$ and $q(nT)$, which are images from two binary streams representing information to be transmitted, the radiofrequency transmitter comprising:

- means of transposition into an intermediate
25 frequency and of digital processing, that provide a first transposition into the digital domain, at an intermediate frequency ω_0 , for said base band signals, and generating, by combination, two signals at the intermediate frequency and in quadrature;

- means of direct conversion, providing a second transposition into the analog domain, after multiplication by a frequency ω_1 , followed by a summation, of said two signals at the intermediate
5 frequency and in quadrature, in a way that generates a resultant signal which is finally modulated around a frequency ω_2 , where $\omega_2 = \omega_0 + \omega_1$.

Therefore, this invention proposes an original architecture for a radiofrequency transmitter that
10 combines the architectures with direct conversion and with frequency transposition, and which provides, in addition, means of digital processing, which provide preprocessing that permits attenuation at the output of the image frequency introduced by the means of
15 transposition into an intermediate frequency. Hence, this new architecture combines the main advantage of the radiofrequency transmitter with direct conversion (no image frequency) with that of the radiofrequency transmitter with frequency transposition (no degradation
20 of the wanted signal), while at the same time avoiding their disadvantages (sensitivity to imperfections, high performance filter).

In the description that follows, it will be shown that this invention operates perfectly if the two
25 channels of the direct conversion means have the same gain and if the sines and cosines supplied by the oscillator included in the direct conversion means do not suffer from poor quadrature forming.

It will also be shown that, in the contrary case, a
30 low power interference signal appears at the image

frequency, but the wanted signal is not degraded in practice. Consequently, it is not essential to use, at the output, a filter attenuating the image frequency of the wanted signal. In any case, when the performance
5 demanded from the transmission chain requires the use of such a filter, the latter can have relaxed constraints since the image frequency is very attenuated and can therefore be easily suppressed. In other words, the quality of the transmitted signal can be preserved
10 without the need for high image filtering constraints. In certain cases, if the constraints are sufficiently relaxed, the image filter may possibly also be integrated with it.

It should be noted that the first frequency
15 transposition and the signal processing are carried out in the digital domain, which enables one to benefit from the precision and the high degree of integration (on silicon for example).

It will also be noted that the radiofrequency
20 transmitter according to the invention has a high degree of integration (for example, on silicon) and advantageously can even be entirely produced in the form of an integrated circuit. In effect, the means of direct conversion are known for their high degree of silicon
25 integration. Furthermore, the level of integration of the means of transposition into an intermediate frequency can be relatively high since it is not necessary to use high performance filters. Finally, the digital processing means can be reduced to an assembly
30 of elements currently used in integrated systems on silicon, and notably in transmitters with frequency

transposition. This assembly of elements comprises, for example, a Numerically Controlled Oscillator or NCO and linear operators (multipliers and adders).

In addition, the extra complexity compared with a direct conversion architecture is negligible.

Finally, passing through a first intermediate frequency ω_0 generated in the digital domain makes possible the attenuation of any possible leak from the conversion oscillator via the mixers.

10 In one advantageous embodiment of the invention, said radiofrequency transmitter additionally comprises means of digitally compensating for imperfections in gain and in phase in said means of direct conversion.

Hence, by ensuring that at the output of the radiofrequency transmitter, the signal at the image frequency is completely attenuated, the performance of the radiofrequency transmitter according to the invention is optimized and the resulting transmitted signal has characteristics close to the ideal case.
15 Thanks to this self-calibrating technique of image annulment, the errors introduced by the analog part (that is to say the means of direct conversion) sensitive to the imperfections, are compensated for in the digital domain.

25 It is important to note that in this particular embodiment, no image frequency filter whatsoever is required. This new architecture for a radiofrequency transmitter therefore operates independently of the chosen carrier frequency and is therefore particularly
30 suitable for multi-standard systems of

radiocommunications. Among the standards possible, one may mention only by way of examples, the Global System for Mobile communications or GSM, the Digital Cellular System 1800 MHz or DCS 1800, the Personal Communication
 5 System or PCS 1900, Digital European Cordless Telecommunications or DECT or the Universal Mobile Telecommunication System or UMTS etc..

Preferably, said analog/digital conversion means have a working frequency substantially identical to the
 10 working frequency of the digital/analog conversion means in said means of direct conversion.

In a preferred way, said means of digital compensation are included in said integrated circuit. Hence, the radiofrequency transmitter according to this
 15 invention can be entirely integrated, for example on silicon.

Brief Description of the Drawings

Other characteristics and advantages of the invention will become apparent on reading the following description of two preferred embodiments of the
 20 invention, given by way of examples for information purposes and being non-limitative and accompanied by the appended drawings in which :

- Figure 1 shows a general diagram of a first embodiment of a radiofrequency transmitter according to
 25 this invention with "simple" image annulment ; and

- Figure 2 shows a general diagram of a second embodiment of a radiofrequency transmitter according to this invention with "self-calibrating" image annulment.

Detailed Description

Therefore the invention relates to a radiofrequency
 30 transmitter of the type supplied with two digital signals in baseband and in quadrature $i(nT)$ and $q(nT)$,

which are images of two binary streams representing information to be transmitted. T is the sample period.

In a traditional way, and whatever the digital modulation used, one is seeking to provide a signal to
5 be transmitted $m(t)$ that can be written :

$$m(t) = i(t) \cdot \cos(\omega t) - q(t) \cdot \sin(\omega t).$$

where $\omega (= 2\pi f)$, the frequency of transmission of the signal (also called the carrier frequency).

10 1. FIRST EMBODIMENT : "SIMPLE" IMAGE ANNULMENT

1.1 PRESENTATION OF THE ARCHITECTURE

A first embodiment of a radiofrequency transmitter according to this invention will now be described making reference to Figure 1.

15 In this first embodiment, the radiofrequency transmitter comprises means 1 of transposition into an intermediate frequency and of digital processing and means 2 of direct conversion.

The means 1 of transposition into an intermediate
20 frequency and of digital processing generate two signals $m_1(t)$ and $m_2(t)$ at an intermediate frequency ω_0 and in quadrature. They comprise:

- a numerically controlled oscillator NCO (not shown) at an intermediate frequency ω_0 , supplying the
25 following signals : $\cos(\omega_0 \cdot nT)$ and $\sin(\omega_0 \cdot nT)$;
- four multipliers 3_1 to 3_4 ; and
- two adders 4_1 to 4_2 .

The multipliers 3_1 to 3_4 and the adders 4_1 and 4_2 are fitted in such a way that the signals $m_1(nT)$ and $m_2(nT)$ are of the form:

$$m_1(nT) = i(nT) \cdot \cos(\omega_0 \cdot nT) - q(nT) \cdot \sin(\omega_0 \cdot nT)$$

5 $m_2(nT) = -i(nT) \cdot \sin(\omega_0 \cdot nT) - q(nT) \cdot \cos(\omega_0 \cdot nT)$

The means 2 of direct conversion generate a resultant signal $m(t)$. They comprise:

- on each of the two channels in quadrature, a digital/analog converter (CNA) 5_1 , 5_2 and a high-stop
10 filter 6_1 , 6_2 , that permits the conversion of the two digital signals $m_1(nT)$ and $m_2(nT)$ into two analog signals $m_1(t)$ and $m_2(t)$;

- a conversion oscillator 7 at a transmission frequency ω_1 , supplying the following signals : $\cos(\omega_1 \cdot t)$
15 and $\sin(\omega_1 \cdot t)$;

- two multipliers 8_1 and 8_2 ;
- one adder 9.

The multipliers 8_1 and 8_2 and the adder 9 are fitted in such a way that the resultant signal $m(t)$ is of the
20 form:

$$m(t) = g_1 \cdot m_1(t) \cdot \cos(\omega_1 t + \theta_1) + g_2 \cdot m_2(t) \cdot \sin(\omega_1 t + \theta_2)$$

where g_1 and g_2 are the respective gains of the two channels in quadrature of the means 2 of direct conversion, and θ_1 and θ_2 are the respective phase shifts
25 of the two channels in quadrature of the means 2 of direct conversion.

As may be found in detail in the description below, it is shown that the resultant signal is finally modulated around a frequency $\omega_2 (= \omega_0 + \omega_1)$.

Optionally, a filter 17 at the image frequency $\omega_2 (= \omega_0 + \omega_1)$, can be placed at the output from the radiofrequency transmitter. This filter 17 may possibly also be included in the integrated circuit in which form the radiofrequency transmitter is produced.

1.2 DESCRIPTION OF THE IDEAL CASE

Therefore, the principle consists of generating two signals $m_1(t)$ and $m_2(t)$ made up of the two channels in quadrature $i(t)$ and $q(t)$.

$$\begin{aligned} m_1(t) &= i(t) \cdot \cos(\omega_0 t) - q(t) \cdot \sin(\omega_0 t) \\ m_2(t) &= -i(t) \cdot \sin(\omega_0 t) - q(t) \cdot \cos(\omega_0 t) \end{aligned} \quad (2)$$

where $\omega_0 (= 2\pi f_0)$ is the first intermediate frequency generated in the digital domain.

Next, the means 2 of direct conversion transpose the two signals around the carrier frequency ω_1 by multiplying them by $\sin(\omega_1 t + \phi)$ and $\cos(\omega_1 t + \phi)$.

The resultant signal $m(t)$ is written in the following way:

$$\begin{aligned} m(t) &= m_1(t) \cdot \cos(\omega_1 t + \phi) + m_2(t) \cdot \sin(\omega_1 t + \phi) \\ &= i(t) \cdot \cos(\omega_0 t + \omega_1 t + \phi) - q(t) \cdot \sin(\omega_0 t + \omega_1 t + \phi) \end{aligned} \quad (3)$$

$$m(t) = i(t) \cdot \cos(\omega_2 t + \phi) - q(t) \cdot \sin(\omega_2 t + \phi) \quad (4)$$

A signal is obtained modulated around the carrier $\omega_2 = \omega_0 + \omega_1$, the particular feature of which is not to have an image frequency around ω_1 . The resultant formula in equation (4) is verified for the ideal case where the transmitter with direct conversion has perfect characteristics. Unfortunately, this is rarely the case.

1.3 DESCRIPTION OF THE REAL CASE

Taking the imperfections into account, the resultant transmitted signal $m(t)$ is written:

$$m(t) = g_1 \cdot m_1(t) \cdot \cos(\omega_1 t + \theta_1) + g_2 \cdot m_2(t) \cdot \sin(\omega_1 t + \theta_2) \quad (5)$$

Equation (2) enables one to write equation (5) that includes $i(t)$ and $q(t)$:

$$\begin{aligned} m(t) &= i(t) \cdot [g_1 \cdot \cos \omega_0 t \cdot \cos(\omega_1 t + \theta_1) - g_2 \cdot \sin \omega_0 t \cdot \sin(\omega_1 t + \theta_2)] \\ &\quad - q(t) \cdot [g_1 \cdot \sin \omega_0 t \cdot \cos(\omega_1 t + \theta_1) + g_2 \cdot \cos \omega_0 t \cdot \sin(\omega_1 t + \theta_2)] \\ m(t) &= \frac{i(t)}{2} \left\{ g_1 [\cos(\omega_0 t - \omega_1 t - \theta_1) + \cos(\omega_0 t + \omega_1 t + \theta_1)] \right. \\ &\quad \left. - g_2 [\cos(\omega_0 t - \omega_1 t - \theta_2) - \cos(\omega_0 t + \omega_1 t + \theta_2)] \right\} \\ &\quad - \frac{q(t)}{2} \left\{ g_1 [\sin(\omega_0 t - \omega_1 t - \theta_1) + \sin(\omega_0 t + \omega_1 t + \theta_1)] \right. \\ &\quad \left. - g_2 [\sin(\omega_0 t - \omega_1 t - \theta_2) - \sin(\omega_0 t + \omega_1 t + \theta_2)] \right\} \quad (6) \\ m(t) &= \frac{i(t)}{2} \left\{ g_1 \cdot \cos(\omega_0 t - \omega_1 t - \theta_1) - g_2 \cdot \cos(\omega_0 t - \omega_1 t - \theta_2) \right\} \\ &\quad + \frac{i(t)}{2} \left\{ g_1 \cdot \cos(\omega_0 t + \omega_1 t + \theta_1) + g_2 \cdot \cos(\omega_0 t + \omega_1 t + \theta_2) \right\} \\ &\quad - \frac{q(t)}{2} \left\{ g_1 \cdot \sin(\omega_0 t - \omega_1 t - \theta_1) - g_2 \cdot \sin(\omega_0 t - \omega_1 t - \theta_2) \right\} \\ &\quad + \frac{q(t)}{2} \left\{ g_1 \cdot \sin(\omega_0 t + \omega_1 t + \theta_1) + g_2 \cdot \sin(\omega_0 t + \omega_1 t + \theta_2) \right\} \end{aligned}$$

In order to simplify the result described by equation (6) we can replace :

$$\begin{aligned} \theta_1 &= \theta - \frac{\Delta\theta}{2} \\ \theta_2 &= \theta + \frac{\Delta\theta}{2} \end{aligned} \quad \text{with } \theta = \frac{\theta_1 + \theta_2}{2} \quad \text{and} \\ \begin{aligned} g_1 &= g - \frac{\Delta g}{2} \\ g_2 &= g + \frac{\Delta g}{2} \end{aligned} \quad \text{with } g = \frac{g_1 + g_2}{2} \quad (7)$$

which means that $m(t)$ can be expressed in the form:

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$$m(t) = \frac{i(t)}{2} \left\{ \begin{aligned} &g \left[\cos\left(\omega_0 t - \omega_1 t - \theta + \frac{\Delta\theta}{2}\right) - \cos\left(\omega_0 t - \omega_1 t - \theta - \frac{\Delta\theta}{2}\right) \right] \\ &- \frac{\Delta g}{2} \left[\cos\left(\omega_0 t - \omega_1 t - \theta + \frac{\Delta\theta}{2}\right) + \cos\left(\omega_0 t - \omega_1 t - \theta - \frac{\Delta\theta}{2}\right) \right] \\ &+ g \left[\cos\left(\omega_0 t + \omega_1 t + \theta - \frac{\Delta\theta}{2}\right) + \cos\left(\omega_0 t + \omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \right] \\ &- \frac{\Delta g}{2} \left[\cos\left(\omega_0 t + \omega_1 t + \theta - \frac{\Delta\theta}{2}\right) - \cos\left(\omega_0 t + \omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \right] \end{aligned} \right\} \\ - \frac{q(t)}{2} \left\{ \begin{aligned} &g \left[\sin\left(\omega_0 t - \omega_1 t - \theta + \frac{\Delta\theta}{2}\right) - \sin\left(\omega_0 t - \omega_1 t - \theta - \frac{\Delta\theta}{2}\right) \right] \\ &- \frac{\Delta g}{2} \left[\sin\left(\omega_0 t - \omega_1 t - \theta + \frac{\Delta\theta}{2}\right) + \sin\left(\omega_0 t - \omega_1 t - \theta - \frac{\Delta\theta}{2}\right) \right] \\ &+ g \left[\sin\left(\omega_0 t + \omega_1 t + \theta - \frac{\Delta\theta}{2}\right) + \sin\left(\omega_0 t + \omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \right] \\ &- \frac{\Delta g}{2} \left[\sin\left(\omega_0 t + \omega_1 t + \theta - \frac{\Delta\theta}{2}\right) - \sin\left(\omega_0 t + \omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \right] \end{aligned} \right\} \quad (8)$$

$$m(t) = i(t) \left\{ \begin{aligned} &-g \sin(\omega_0 t - \omega_1 t - \theta) \sin\left(\frac{\Delta\theta}{2}\right) - \frac{\Delta g}{2} \cos(\omega_0 t - \omega_1 t - \theta) \cos\left(\frac{\Delta\theta}{2}\right) \\ &+ g \cos(\omega_0 t + \omega_1 t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) - \frac{\Delta g}{2} \sin(\omega_0 t + \omega_1 t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) \end{aligned} \right\} \quad (9)$$

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$$- q(t) \left\{ \begin{aligned} &g \cos(\omega_0 t - \omega_1 t - \theta) \sin\left(\frac{\Delta\theta}{2}\right) - \frac{\Delta g}{2} \sin(\omega_0 t - \omega_1 t - \theta) \cos\left(\frac{\Delta\theta}{2}\right) \\ &+ g \sin(\omega_0 t + \omega_1 t + \theta) \cos\left(\frac{\Delta\theta}{2}\right) + \frac{\Delta g}{2} \cos(\omega_0 t + \omega_1 t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) \end{aligned} \right\}$$

By bringing in the carrier frequency $\omega_2 = \omega_1 + \omega_0$
and its image frequency $\omega_{-2} = \omega_1 - \omega_0$:

$$m(t) = i(t) \left\{ \begin{aligned} &g \sin(\omega_{-2} t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) - \frac{\Delta g}{2} \cos(\omega_{-2} t + \theta) \cos\left(\frac{\Delta\theta}{2}\right) \\ &+ g \cos(\omega_2 t + \theta) \cos\left(\frac{\Delta\theta}{2}\right) - \frac{\Delta g}{2} \sin(\omega_2 t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) \end{aligned} \right\} \quad (10)$$

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$$-q(t) \left\{ \begin{aligned} &g \cdot \cos(\omega_2 t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) + \frac{\Delta g}{2} \sin(\omega_2 t + \theta) \cos\left(\frac{\Delta\theta}{2}\right) \\ &+ g \cdot \sin(\omega_2 t + \theta) \cos\left(\frac{\Delta\theta}{2}\right) + \frac{\Delta g}{2} \cos(\omega_2 t + \theta) \sin\left(\frac{\Delta\theta}{2}\right) \end{aligned} \right\}$$

$$m(t) = g \cdot \cos\left(\frac{\Delta\theta}{2}\right) [i(t) \cdot \cos(\omega_2 t + \theta) - q(t) \cdot \sin(\omega_2 t + \theta)] \\ - \frac{\Delta g}{2} \sin\left(\frac{\Delta\theta}{2}\right) [i(t) \cdot \sin(\omega_2 t + \theta) + q(t) \cdot \cos(\omega_2 t + \theta)]$$

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(11)

$$+ g \cdot \sin\left(\frac{\Delta\theta}{2}\right) [i(t) \cdot \sin(\omega_2 t + \theta) - q(t) \cdot \cos(\omega_2 t + \theta)] \\ - \frac{\Delta g}{2} \cos\left(\frac{\Delta\theta}{2}\right) [i(t) \cdot \cos(\omega_2 t + \theta) + q(t) \cdot \sin(\omega_2 t + \theta)]$$

The resultant signal $m(t)$ is therefore constituted by :

10

- a wanted signal (modulated about the carrier ω_2),
weighted by a gain equal to $g \cdot \cos\left(\frac{\Delta\theta}{2}\right)$;

- an undesirable component, whose amplitude is of
the order of $\frac{\Delta g}{2} \sin\left(\frac{\Delta\theta}{2}\right)$;

15

- an image in ω_2 (due to the imperfections), the
power of which depends on the difference in gain Δg and
in phase $\Delta\theta$ between the two channels.

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The result from equation (11) shows that the
imperfections in gain and in phase generate a parasite
component in ω_2 of power sufficiently low to be easily
filtered. Contrary to this, the imperfections have very
little influence on the quality of the wanted signal.

If a gain error $\Delta g = 3\%$ and a phase error (quadrature) $\Delta\theta = 3^\circ$ are chosen, the C/I of the wanted signal (power of the signal / power of the interference at frequency ω_2) is 68 dBc, instead of 28 dBc for an architecture with traditional direct conversion. The power level of the interference present at the image frequency ω_{-2} is about 28 dB below the wanted signal while it would be 25 times higher with a traditional frequency transposition structure.

Compared to the other architectures, this original system offers the following advantages:

- an identical gain for the channels $i(t)$ and $q(t)$;
- negligible degradation of the wanted signal ($\approx \Delta g \cdot \Delta\theta / 4$);
- a highly attenuated image frequency which can be suppressed with a relaxed constraint filter;
- reduced complexity compared with a direct conversion transmitter thanks to signal processing being carried out in the digital domain.

Furthermore, passing through a first intermediate frequency $FI(\omega_0)$ generated in the digital domain enables one to attenuate any possible leakage from the conversion oscillator via the mixers.

2. SECOND EMBODIMENT : "SELF-CALIBRATING" IMAGE ANNULMENT

2.1 DESCRIPTION OF THE ARCHITECTURE

A second embodiment of a radiofrequency transmitter according to this invention will now be described with reference to Figure 2.

In effect, in order to go further with the radiofrequency transmitter according to the invention it is proposed that gain and phase errors introduced in the direct conversion means 2 be compensated for digitally. Hence, at the output, the signal present at the image frequency will be completely attenuated.

This second embodiment differs from the first embodiment (described above with reference to Figure 1) in that it additionally comprises means 10, 11 of digitally compensating for imperfections in gain Δg and in phase $\Delta \theta$ of the direct conversion means 2. These compensation means themselves comprise means 10 of estimating the imperfections Δg and $\Delta \theta$, and means 11 of applying a correction to the two signals $m_1(t)$ and $m_2(t)$ in a way that generates two corrected signals $m_{1c}(t)$ and $m_{2c}(t)$.

In the embodiment shown in Figure 2, the means 10 of estimating the imperfections comprise :

- transposition means 12, providing a third transposition in the analog domain, by multiplication of the resultant signal $m(t)$ by the transmission frequency ω_1 , in a way that generates an intermediate signal : $m'_3(t) = g_3 \cdot m(t) \cdot \cos(\omega_1 t + \theta_1)$, where g_3 is the gain introduced by the transposition means 12, the filtering means 13 and the analog/digital A/N conversion means 14.

- a high stop filter 13, providing filtering of the intermediate signal $m'_3(t)$ and generating an intermediate filtered signal $m'(t)$;

- an analog/digital converter (CAN) 14, enabling one to convert the intermediate filtered signal $m'(t)$ into digital;

- means 15 of calculating imperfections in gain Δg and in phase $\Delta \theta$ from the digital filtered intermediate signal $m'(t)$.

10 It should be noted that the means 1 of transposition into intermediate frequency and of digital processing, the means 15 of calculating the imperfections and the means 11 of applying a correction to the two signals $m_1(t)$ and $m_2(t)$ can be included in one and the same digital signal processor (or DSP) 16.

The operation of this second embodiment of the radiofrequency transmitter can be broken down into three successive phases, namely;

- recovery of the resultant transmitted signal $m(t)$;

- calculation of the correction coefficients Δg and $\Delta \theta$;

- calculation of the resultant corrected signal $m_c(t)$.

25 These three phases will now be described in succession, in paragraphs 2.2 to 2.4 respectively.

1.2 RECOVERY OF THE RESULTANT TRANSMITTED SIGNAL

The resultant signal $m(t)$ is multiplied by the frequency ω_1 of the conversion oscillator 7 (the latter is included in the direct conversion means 2). Hence $m(t)$ is transposed to a lower fixed frequency, before
5 analog/digital conversion.

The resultant signal is written :

$$m'_3(t) = g_3 \cdot m(t) \cdot \cos\left(\omega_1 t + \theta - \frac{\Delta\theta}{2}\right)$$

By developing the product above and assuming that $g_3=1$, $m'_3(t)$ becomes:

$$\begin{aligned} 10 \quad m'_3(t) = & g \cdot \cos\left(\frac{\Delta\theta}{2}\right) \left\{ \frac{i(t)}{2} \left[\cos\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + \cos\left(2\omega_1 t + \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right. \\ & \left. - \frac{q(t)}{2} \left[\sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + \sin\left(2\omega_1 t + \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right\} \\ & - \frac{\Delta g}{2} \sin\left(\frac{\Delta\theta}{2}\right) \left\{ \frac{i(t)}{2} \left[\sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + \sin\left(2\omega_1 t + \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right. \\ & \left. + \frac{q(t)}{2} \left[\cos\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + \cos\left(2\omega_1 t + \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right\} \\ & + g \cdot \sin\left(\frac{\Delta\theta}{2}\right) \left\{ \frac{i(t)}{2} \left[\sin\left(-\omega_0 t + \frac{\Delta\theta}{2}\right) + \sin\left(2\omega_1 t - \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right. \\ & \left. - \frac{q(t)}{2} \left[\cos\left(-\omega_0 t + \frac{\Delta\theta}{2}\right) + \cos\left(2\omega_1 t - \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right\} \\ & - \frac{\Delta g}{2} \cos\left(\frac{\Delta\theta}{2}\right) \left\{ \frac{i(t)}{2} \left[\cos\left(-\omega_0 t + \frac{\Delta\theta}{2}\right) + \cos\left(2\omega_1 t - \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right. \\ & \left. + \frac{q(t)}{2} \left[\sin\left(-\omega_0 t + \frac{\Delta\theta}{2}\right) + \sin\left(2\omega_1 t - \omega_0 t + 2\theta - \frac{\Delta\theta}{2}\right) \right] \right\} \end{aligned}$$

(12)

15 The high stop filtering (filter 13) suppresses the components $2\omega_1 t \pm \omega_0 t$ and gives :

$$m'(t) = g \cos\left(\frac{\Delta\theta}{2}\right) \left[\frac{i(t)}{2} \cos\left(\omega_0 t + \frac{\Delta\theta}{2}\right) - \frac{q(t)}{2} \sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) \right]$$

$$-\frac{\Delta g}{2}\sin\left(\frac{\Delta\theta}{2}\right)\left[\frac{i(t)}{2}\sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + \frac{q(t)}{2}\cos\left(\omega_0 t + \frac{\Delta\theta}{2}\right)\right] \quad (13)$$

$$-g\sin\left(\frac{\Delta\theta}{2}\right)\left[\frac{i(t)}{2}\sin\left(\omega_0 t - \frac{\Delta\theta}{2}\right) + \frac{q(t)}{2}\cos\left(\omega_0 t - \frac{\Delta\theta}{2}\right)\right]$$

$$-\frac{\Delta g}{2}\cos\left(\frac{\Delta\theta}{2}\right)\left[\frac{i(t)}{2}\cos\left(\omega_0 t - \frac{\Delta\theta}{2}\right) - \frac{q(t)}{2}\sin\left(\omega_0 t - \frac{\Delta\theta}{2}\right)\right]$$

5

$$m'(t) = g\cos\left(\frac{\Delta\theta}{2}\right)\left\{\frac{i(t)}{2}\left[\cos(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) - \sin(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right] - \frac{q(t)}{2}\left[\sin(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) + \cos(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right]\right\}$$

$$-\frac{\Delta g}{2}\sin\left(\frac{\Delta\theta}{2}\right)\left\{\frac{i(t)}{2}\left[\sin(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) + \cos(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right] + \frac{q(t)}{2}\left[\cos(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) - \sin(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right]\right\}$$

$$-g\sin\left(\frac{\Delta\theta}{2}\right)\left\{\frac{i(t)}{2}\left[\sin(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) - \cos(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right] + \frac{q(t)}{2}\left[\cos(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) + \sin(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right]\right\}$$

$$-\frac{\Delta g}{2}\cos\left(\frac{\Delta\theta}{2}\right)\left\{\frac{i(t)}{2}\left[\cos(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) + \sin(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right] - \frac{q(t)}{2}\left[\sin(\omega_0 t)\cos\left(\frac{\Delta\theta}{2}\right) - \cos(\omega_0 t)\sin\left(\frac{\Delta\theta}{2}\right)\right]\right\} \quad (14)$$

10

$$m'(t) = g\left\{\frac{i(t)}{2}\left[\cos(\omega_0 t)\cos^2\left(\frac{\Delta\theta}{2}\right) - \sin(\omega_0 t)\frac{\sin(\Delta\theta)}{2}\right] - \frac{q(t)}{2}\left[\sin(\omega_0 t)\cos^2\left(\frac{\Delta\theta}{2}\right) + \cos(\omega_0 t)\frac{\sin(\Delta\theta)}{2}\right]\right\}$$

$$\begin{aligned}
& -\frac{\Delta g}{2} \left\{ \frac{i(t)}{2} \left[\sin(\omega_0 t) \frac{\sin(\Delta\theta)}{2} + \cos(\omega_0 t) \sin^2\left(\frac{\Delta\theta}{2}\right) \right] \right. \\
& \quad \left. + \frac{q(t)}{2} \left[\cos(\omega_0 t) \frac{\sin(\Delta\theta)}{2} - \sin(\omega_0 t) \sin^2\left(\frac{\Delta\theta}{2}\right) \right] \right\} \\
& -g \left\{ \frac{i(t)}{2} \left[\sin(\omega_0 t) \frac{\sin(\Delta\theta)}{2} - \cos(\omega_0 t) \sin^2\left(\frac{\Delta\theta}{2}\right) \right] \right. \\
& \quad \left. + \frac{q(t)}{2} \left[\cos(\omega_0 t) \frac{\sin(\Delta\theta)}{2} + \sin(\omega_0 t) \sin^2\left(\frac{\Delta\theta}{2}\right) \right] \right\} \\
& -\frac{\Delta g}{2} \left\{ \frac{i(t)}{2} \left[\cos(\omega_0 t) \cos^2\left(\frac{\Delta\theta}{2}\right) + \sin(\omega_0 t) \frac{\sin(\Delta\theta)}{2} \right] \right. \\
& \quad \left. - \frac{q(t)}{2} \left[\sin(\omega_0 t) \cos^2\left(\frac{\Delta\theta}{2}\right) - \cos(\omega_0 t) \frac{\sin(\Delta\theta)}{2} \right] \right\} \quad (15)
\end{aligned}$$

$$\begin{aligned}
5 \quad m'(t) = g \left\{ \frac{i(t)}{2} [\cos(\omega_0 t) - \sin(\omega_0 t) \sin(\Delta\theta)] - \frac{q(t)}{2} [\sin(\omega_0 t) + \cos(\omega_0 t) \sin(\Delta\theta)] \right\} \\
(16)
\end{aligned}$$

$$-\frac{\Delta g}{2} \left\{ \frac{i(t)}{2} [\cos(\omega_0 t) + \sin(\omega_0 t) \sin(\Delta\theta)] - \frac{q(t)}{2} [\sin(\omega_0 t) - \cos(\omega_0 t) \sin(\Delta\theta)] \right\}$$

$$m'(t) = \left\{ \frac{i(t)}{2} \left[g - \frac{\Delta g}{2} \right] - \frac{q(t)}{2} \left[g + \frac{\Delta g}{2} \right] \sin(\Delta\theta) \right\} \cos(\omega_0 t)$$

$$10 \quad (17)$$

$$-\left\{ \frac{i(t)}{2} \left[g + \frac{\Delta g}{2} \right] \sin(\Delta\theta) + \frac{q(t)}{2} \left[g - \frac{\Delta g}{2} \right] \right\} \sin(\omega_0 t)$$

$$m'(t) = i'(t) \cos(\omega_0 t) - q'(t) \sin(\omega_0 t) \quad \text{with} \quad \begin{cases} i'(t) = a.i(t) - b.q(t) \\ q'(t) = b.i(t) + a.q(t) \end{cases}$$

$$(18)$$

$$15 \quad a = \frac{2g - \Delta g}{4}, \quad b = \frac{2g + \Delta g}{4} \sin(\Delta\theta)$$

From equation (18), one seeks to extract the coefficients 'a' and 'b' so as to deduce from it the values of Δg and $\Delta\theta$. Knowing that $i^2(t) + q^2(t) = 1$, one has

$$\begin{aligned} a &= i(t).i'(t) + q(t).q'(t) \\ b &= i(t).q'(t) - q(t).i'(t) \end{aligned} \quad (19)$$

5 In the real case where $g_3 \neq 0$, the coefficients 'a' and 'b' are written:

$$a = g_3 \cdot \frac{2g - \Delta g}{4} \quad \text{and} \quad b = g_3 \cdot \frac{2g + \Delta g}{4} \sin \Delta\theta \quad (20)$$

1.3 CALCULATION OF THE CORRECTION COEFFICIENTS

10 Knowing the theoretical values of the gains 'g' and 'g₃', one can calculate Δg , $\Delta\theta$ and the real value of g_3 from the coefficients 'a' and 'b'. Equation (20) gives us:

$$a + b = \frac{g_3}{4} [2g(1 + \sin \Delta\theta) - \Delta g(1 - \sin \Delta\theta)] \quad (21)$$

15 Assuming that, in a first approximation, $\sin \Delta\theta \approx 0$ and $\Delta g \ll g$, an estimation of the gain g_3 can be deduced:

$$g'_3 = \frac{2(a+b)}{g} = \frac{2}{g} [i'(t) + q'(t)][i(t) - q(t)] \quad (22)$$

20 On keeping the approximation $\sin \Delta\theta \approx 0$ and knowing the theoretical value for g_3 , one can rapidly determine Δg :

$$\Delta g \approx \frac{2g}{g_3} (g_3 - g'_3) = 2g - \frac{4}{g_3} [i'(t) + q'(t)][i(t) - q(t)] \quad (23)$$

On introducing the gain calculated in (22), the coefficient $\Delta\theta$ is deduced from equation (20) with the hypothesis that $\sin\Delta\theta \approx \Delta\theta$ and $\Delta g \cdot \sin\Delta\theta \approx 0$:

$$\Delta\theta \approx \frac{b}{g g_3} = \frac{1}{g \cdot g_3} [i(t) \cdot q'(t) - q(t) \cdot i'(t)] \quad (24)$$

By choosing values to the value 2 for the theoretical gains 'g' and 'g3', the calculation of the correction coefficients is simplified, avoiding an expensive division in silicon.

1.4 CALCULATION OF THE RESULTANT CORRECTED SIGNAL

After calculation of the correction coefficients Δg and $\Delta\theta$, the new corrected transmission signal $m_c(t)$ must be constructed:

$$m_c(t) = m_{1c}(t) \cdot \left(g - \frac{\Delta g}{2}\right) \cos\left(\omega_1 t + \theta - \frac{\Delta\theta}{2}\right) + m_{2c}(t) \cdot \left(g + \frac{\Delta g}{2}\right) \sin\left(\omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \quad (25)$$

where $m_{1c}(t)$ and $m_{2c}(t)$ are the two channels corrected for gain and phase:

$$m_{1c}(t) = \frac{1}{\left(1 - \frac{\Delta g}{2g}\right)} \left[i(t) \cdot \cos\left(\omega_0 t - \frac{\Delta\theta}{2}\right) - q(t) \cdot \sin\left(\omega_0 t - \frac{\Delta\theta}{2}\right) \right] \quad (26)$$

$$m_{2c}(t) = \frac{-1}{\left(1 + \frac{\Delta g}{2g}\right)} \left[i(t) \cdot \cos\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + q(t) \cdot \sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) \right]$$

By developing equation (25) one arrives at:

$$m_c(t) = i(t) \cdot \cos\left(\omega_1 t + \theta - \frac{\Delta\theta}{2}\right) \cdot \cos\left(\omega_1 t - \frac{\Delta\theta}{2}\right) - q(t) \cdot \cos\left(\omega_1 t + \theta - \frac{\Delta\theta}{2}\right) \cdot \sin\left(\omega_1 t - \frac{\Delta\theta}{2}\right) \quad (27)$$

$$- i(t) \cdot \sin\left(\omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \cdot \sin\left(\omega_1 t + \frac{\Delta\theta}{2}\right) - q(t) \cdot \sin\left(\omega_1 t + \theta + \frac{\Delta\theta}{2}\right) \cdot \cos\left(\omega_1 t + \frac{\Delta\theta}{2}\right)$$

$$\begin{aligned} m_c(t) = & \frac{i(t)}{2} [\cos(\omega_1 t - \omega_0 t + \theta) + \cos(\omega_1 t + \omega_0 t + \theta - \Delta\theta)] \\ & + \frac{q(t)}{2} [\sin(\omega_1 t - \omega_0 t + \theta) - \sin(\omega_1 t + \omega_0 t + \theta - \Delta\theta)] \\ 5 \quad & - \frac{i(t)}{2} [\cos(\omega_1 t - \omega_0 t + \theta) - \cos(\omega_1 t + \omega_0 t + \theta + \Delta\theta)] \\ & - \frac{q(t)}{2} [\sin(\omega_1 t - \omega_0 t + \theta) + \sin(\omega_1 t + \omega_0 t + \theta + \Delta\theta)] \end{aligned} \quad (28)$$

$$\begin{aligned} m_c(t) = & \frac{i(t)}{2} [\cos(\omega_1 t + \omega_0 t + \theta - \Delta\theta) + \cos(\omega_1 t + \omega_0 t + \theta + \Delta\theta)] \\ & - \frac{q(t)}{2} [\sin(\omega_1 t + \omega_0 t + \theta - \Delta\theta) + \sin(\omega_1 t + \omega_0 t + \theta + \Delta\theta)] \end{aligned} \quad (29)$$

10

$$m_c(t) = [i(t) \cos(\omega_1 t + \omega_0 t + \theta) - q(t) \sin(\omega_1 t + \omega_0 t + \theta)] \cos \Delta\theta \quad (30)$$

By again substituting $\omega_2 = \omega_1 + \omega_0$, one again finds the expression for the signal $m(t)$ formulated in the ideal case (equation 4), with $g = 1$). The correction system is simplified without degrading the signal quality since this again is applied to both channels $i(t)$ and $q(t)$. If $\Delta\theta = 5^\circ$, the resultant error is about 0.4% on the amplitude of the transmitted signal.

The simplified expression for the two channels $m_{1c}(t)$ and $m_{2c}(t)$ corrected for gain and for phase is written:

$$m_{1c}(t) = \left(1 + \frac{\Delta g}{2g}\right) \cdot \left[i(t) \cdot \cos\left(\omega_0 t - \frac{\Delta\theta}{2}\right) - q(t) \cdot \sin\left(\omega_0 t - \frac{\Delta\theta}{2}\right) \right]$$

$$m_{2c}(t) = -\left(1 - \frac{\Delta g}{2g}\right) \left[i(t) \cdot \sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) + q(t) \cdot \sin\left(\omega_0 t + \frac{\Delta\theta}{2}\right) \right] \quad (31)$$

In other words the means 11 of applying a correction to the two signals $m_1(t)$ and $m_2(t)$ apply:

- to the first channel : a gain equal to $(1 + \Delta g/2g)$ and a phase shift equal to $(-\Delta\theta/2)$;
- to the second channel : a gain equal to $(1 - \Delta g/2g)$ and a phase shift equal to $(+\Delta\theta/2)$.

In this way all division operations for the calculation of the corrected signal are avoided ; within the hypothesis where the theoretical value for the gain 'g' is chosen in such a way that it is a multiple of a power of 2.

The algorithms for calculating Δg and $\Delta\theta$ have been successfully simulated : the error is compensated after 5 iterations at the most, according to the orders of magnitude of Δg and $\Delta\theta$ (up to 10% and 8° respectively) and with an error ranging up to 12% on the value of g_3 .

Throughout the detailed description above of two particular embodiments, the new architecture of a radiofrequency transmitter according to this invention has been described.

It will be recalled that it combines the advantages of a transmitter with direct conversion (no image frequency) without having its disadvantages (no degradation of the wanted signal). Thanks to the self-calibrating system, the errors, introduced through the analog part sensitive to the imperfections, are compensated for in the digital domain. Hence the

resultant signal which is transmitted has characteristics close to the ideal case.

The signal processing functions are carried out in the digital domain so as to exploit the precision and the high degree of integration on silicon. The analog/digital converter (CAN) 14 is, for example of the "delta-sigma pass band" type, whose working frequency is preferably identical to that of the two digital/analog converters 5_1 and 5_2 . The analog high stop filter 13 has relaxed constraints : a filter of order 2 is sufficient in most cases.

The radiofrequency transmitter according to the invention provides relatively low complexity compared with the remainder of the transmission chain and has the advantage of being able to be completely integrated on silicon.